GAS ANALYSIS TECHNIQUE FOR GAS INSULATED SWITCHGEAR CONDITION MONITORING AND DIAGNOSIS

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To the Almighty God the creator of the whole universe.

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ABSTRACT

Sulphur hexafluoride gas insulated switchgear (GIS) is widely used in electrical power supply system and therefore needs regular preventive maintenance. Usual diagnosis methods used are based on acoustic, optical, electrical and ultra high frequency techniques. A new method with great potential is using gas by-products analysis. Previous gas by-products research is confined to a plane-plane electrode instead of typical coaxial GIS configuration, a limited number of defect types and the by-products analysis using gas chromatography. In this thesis, partial discharge experiments using a purposely designed coaxial GIS chamber were carried out to expand the diagnosis database for a new set of simulated defects represented by three categories, namely sole defect, hybrid defect, and material dependent defect. A total of eight defects namely, free conducting particle, electrode to dielectric void, electrode protrusion, fixed particle aluminium on spacer, fixed copper particle on spacer, electrode protrusion-fixed copper particle hybrid, electrode protrusion-free copper particle hybrid, and electrode to dielectric void-free copper particle hybrid were simulated. In each experiment lasting up to 50 hours, continually applied voltage at 0.2 MPa pressure, samples of gas by-products were taken at 10 hour intervals for an off-line Fourier transform infrared spectrometer gas analyses. A total of 12 gas by-products due to partial discharge activity in all defects were detected. Arranged according to significance, these are hexafluoroethane, sulphur dioxide, sulfuryl fluoride, octafluoropropane, silicon tetrafluoride, thionyl fluoride, carbon monoxide, disulfur decafluoride, hydrogen fluoride, tetrafluoromethane, carbonyl sulphide and tetrafluoride. Arranged according to significance, the most harmful gases are produced by the defects such as electrode protrusion-fixed copper particle hybrid, fixed copper particle, electrode protrusion-free copper particle hybrid and electrode protrusion. The type, number, concentration and chemical stability of by-product gases are found to be closely correlated to the type of defect. Further analyses using pattern recognition with eight algorithms based on the presence and concentration of the gas by-products were carried out. The random forest algorithm successfully recognises a given defect with an accuracy of 87.5%. The performance of the random forest algorithm is 1.5 times better than the next best algorithm. This research illustrates the feasibility and applicability of an effective GIS diagnostic using gas by-products analyses, in particular, using the random forest pattern recognition.

ABSTRAK

Gas penebat perkakas suis (GIS) sulfur hexafluorida digunakan secara meluas dalam sistem bekalan kuasa elektrik dan oleh yang demikian ia memerlukan penyelenggaraan pencegahan yang kerap. Kaedah diagnosis yang biasa digunakan adalah berasaskan teknik-teknik akustik, optik, elektrik dan frekuensi ultra tinggi. Kaedah baru yang berpotensi besar adalah dengan menggunakan analisis gas produk sampingan. Penyelidikan gas produk sampingan sebelum ini terhad kepada elektrod satah-satah dan bukannya konfigurasi kabel sepaksi untuk GIS, bilangan jenis kecacatan yang terhad, dan analisis produk sampingan menggunakan kromatografi gas. Dalam tesis ini, ujikaji discas separa menggunakan GIS sepaksi koaksial direka untuk memperluaskan lagi pangkalan data diagnosis untuk satu set kecacatan baru yang diwakili oleh tiga kategori, iaitu kecacatan tunggal, kecacatan hibrid dan kecacatan yang bergantung kepada jenis bahan. Lapan kecacatan yang digunakan adalah zarah bebas, rongga dielektrik ke elektrod, penonjolan elektrod, zarah tetap aluminium pada penjarak, zarah tembaga tetap pada penjarak, hibrid zarah tembaga tetap-penonjolan elektrod, hibrid zarah tembaga bebas-penonjolan elektrod dan hibrid zarah tembaga bebas-rongga dielektrik ke elektrod. Dalam setiap eksperimen yang berlanjutan sehingga 50 jam, voltan berterusan dikenakan pada tekanan 0.2 MPa, sampel gas diambil selang 10 jam bagi analisis gas spektrometer jelmaan Fourier inframerah secara luar-talian. Sejumlah dua belas gas produk sampingan disebabkan oleh aktiviti discas separa untuk semua kecacatan telah dikesan. Diatur mengikut kepentingannya, produk sampingan terhasil adalah heksafluoretana, sulfur dioksida, sulfuril fluorida, oktafloropropana, silikon tetrafluorida, tionil fluorida, karbon monoksida, disulfur dekafluorida, hidrogen fluorida, tetrafluorometan, karbonil sulfida dan tetrafluorida. Dirumuskan mengikut kepentingannya, gas yang paling berbahaya dihasilkan oleh kecacatan seperti hibrid penonjolan elektrod-zarah tembaga tetap, zarah tembaga tetap, hibrid penonjolan elektrod-zarah tembaga bebas dan penonjolan elektrod. Jenis, bilangan, ketumpatan dan kestabilan kimia gas produk sampingan didapati berkait dengan jenis kecacatan. Analisis lanjut menggunakan pengenalan corak dengan tujuh algoritma berdasarkan kehadiran dan ketumpatan gas produk sampingan dijalankan. Algoritma hutan rawak berjaya mengenal pasti kecacatan yang dianalisis dengan ketepatan 87.5%. Prestasi algoritma hutan rawak adalah 1.5 kali lebih baik daripada algoritma terbaik seterusnya. Kajian ini menggambarkan kebolehlaksanaan dan kebolehgunaan diagnostik GIS yang berkesan menggunakan analisis gas produk sampingan, khususnya menggunakan pengenalan corak hutan rawak.

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LIST OF ABBREVIATIONS

BIL	-	Basic lighting impulse withstand level
FTIR	-	Fourier transform infrared
GC	-	Gas chromatography
GIS	-	Gas insulated switchgear
MPa	-	Mega pascal
PD	-	Partial discharge
ppmv	-	Part per million volume
UHF	-	Ultra-high frequency
UV	-	Ultraviolet
μl	-	Micro litre

LIST OF SYMBOLS

CF_4	-	Carbon tetrafluoride
C_2F_6	-	Hexafluoroethane
C_3F_8	-	Octafluoropropane
CO	-	Carbon monoxide
CO_2	-	Carbon dioxide
COS	-	Carbonyl sulphide
HF	-	Hydrogen fluoride
HO_2	-	Water
O_2	-	Oxygen
SF	-	Sulphur fluoride
SF_2	-	Sulphur difluoride
SF_3	-	Sulphur trifluoride
SF_4	-	Sulphur tetrafluoride
SF_5	-	Sulphur pentafluoride
SF_6	-	Sulphur hexafluoride
S_2F_{10}	-	Disulfur decafluoride
SiF_4	-	Silicon tetrafluoride
SO_2	-	Sulphur dioxide
SOF_2	-	Thionyl fluoride
SOF_4	-	Thionyl tetrafluoride
SO_2F_2	-	Sulphuryl fluoride

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CHAPTER 1

INTRODUCTION

1.1 Research Background

In any modern society, the social welfare and economic development depend exclusively on the availability of reliable and cheap supply of functional electrical energy. Extensive electrical power system installation network at high voltage in industrialized countries have been built and in developing countries, they are being constructed at an ever-increasing rate for the purpose of transporting electrical energy or power to consumers (industries, research laboratories, homes, and etcetera) for the sustenance of modern civilization [1]. A large amount of electrical power is generated, transmitted and distributed by the power system network over a long distance is best accomplished using high voltage for achieving efficiency, reliability, and economy, thus high voltage equipment (including gas insulated switchgear) are required. In short, high voltage equipment serve as the backbone of a modern power system [2, 3].

Gas insulated switchgear (GIS) is an electromechanical device that comprises the combination of electrical switches, fuses, circuit breakers, current and capacitive voltage transformers, and etcetera, that is used to control, protect and isolate various other high voltage equipment. A switchgear is also used to de-energize high voltage equipment in a power system network to enable fault of all types to be rectified [4, 5].

Gas insulated switchgear is one of the main devices of the electricity transmission and distribution infrastructure that is used to transfer power from power stations to consumers because of its high reliability and performance, compact in dimension, non-explosive, long lifespan (about 40-50 years), low maintenance requirements during its whole lifetime, outstanding compatibility with the environment, and ability to interrupt fault current in a power system network. Furthermore, its operation is noiseless and well insulated against external interferences, such as changes in weather or electromagnetic environment [6-10]. The increase in demand for electricity and the growing energy density in the metropolitan areas have made it necessary to extend the high voltage network right up to the consumer unit in an economical manner while ensuring a high degree of quality and reliability of supply. Gas insulated switchgear in gas insulated substation provides the best solution to this challenge [11].

A gas insulated switchgear uses sulphur hexafluoride (SF_6) gas as an insulant and coolant in view of the fact that it has superior dielectric properties with excellent arc quenching properties compared to air and vacuum [12-16]. SF_6 gas is inert in nature, odourless, colourless, tasteless, chemically stable, non-toxic, non-inflammable and has high vapour pressure (about 21 bar at ambient temperature) [7, 17-20]. It can be used down to -35 °C without liquefaction occurring at pressures typical to its application (about 5 bar) [21]. In addition to its high dielectric strength, it also has good thermal transfer characteristics. SF_6 gas has high (three times that of air) and reasonably constant dielectric strength over a wide range of frequencies. At about 6 bar pressure, its dielectric strength is approximately equal to that of the transformer oil [21].

Although SF_6 has high and constant dielectric strength, it is a brittle gas. This means ionization will build up very rapidly if the critical field strength of SF_6, which is at 89 kV/cm bar, is exceeded during a GIS operation [21]. In practice, this can happen in the vicinity of any small defect, such as due to a contamination in the form of a free conducting particle or a fixed conducting particle on the surface of the GIS spacer, a protrusion or a sharp point on the high voltage or ground electrodes, and a gap or void at the electrode or dielectric interface [11, 21]. These defects will cause partial discharge to occur and its characteristics is dependent on the nature of a particular defect. The partial discharge which occurs due to the local field enhancement may eventually result in the lowering of the insulation maximum operating stress to about 20-80 % of the designed value, and hence, premature failure of GIS [22]. Such failures are sometimes sudden, catastrophic and almost include irreversible internal damage of the system resulting in power outages in the system network that in turn paralyze economic and other activities, incur personal and environmental hazards, and incur high cost of equipment replacement. Therefore, being one of the critical assets, the GIS equipment should be monitored closely and continuously using a reliable and effective technique to assess its operating condition and to diagnose fault early so as to ensure its maximum uptime [23].

1.2 Research Motivation

About 85% of GIS disruptive failure is caused by partial discharge [1, 15, 24]. The failure of live assets is often sudden and catastrophic, with the release of large amounts of energy, leading to explosion and fire resulting in an unrepairable damage to substation equipment, injury or death of personnel working in the substation, and a power outage that will paralyze economic, social, educational, military, security and medical activities. When a dielectric failure occurs in the GIS, the arc will not be extinguished by the insulant gas; this will lead to an internal build up pressure that will drill a hole in the metal wall of the GIS due to the concentration of the arcing thereby causing SF_6 gas that is a highly potent greenhouse gas to leak into the atmosphere, then causing global warming.

Sulphur hexafluoride (SF_6) is a highly potent greenhouse gas with a global warming potential of about 24,000 times greater than carbon dioxide (CO_2) [17, 25]. SF_6 gas also has an atmospheric lifespan of about 3,200 years, so it will contribute to global warming for a very long time. One pound of SF_6 gas has the global warming equivalent of 11 tonnes of CO_2 [13, 17, 25-27].

Under high-temperature conditions, SF_6 gas decomposes into by-products that are toxic and corrosive. The decomposition by-products can exist when SF_6 gas is exposed to spark discharge, partial discharge, and switching arc. These by-products are in the form of gases or powders. It can affect human health and cause the following ill health in humans: irritation to the eyes, nose, and throat, pulmonary oedema and other lungs damage, skin and eye burns, nasal congestion, bronchitis and body rashes [13, 28-33].

In order to avert the occurrence of the above-stated problems, researchers in the world employed techniques to monitor and diagnose partial discharge in GIS. These techniques are photo diagnostic technique, acoustic diagnostic technique, electrical diagnostic technique, ultra-high frequency (UHF) diagnostic technique, and chemical by-product diagnostic technique [1, 15].

Photo, acoustic, electrical and UHF diagnostic techniques are based on the measurement of energy released by the PD activities. Among the released energy are in the form of electromagnetic and acoustic emissions. The magnitude of the energy released can be correlated with the level of SF_6 deterioration. Even though these methods perform effectively to some extent, the bottleneck of these methods is the ingress of external interferences, such as noise and electromagnetic interference. The interferences directly affect the sensitivity and reliability of the acquired PD data [34, 35]. Furthermore, these methods can be likened to as symptoms diagnostic techniques since the measurements are based on only the released PD energy. Hence, there is a need for an effective and more reliable technique for condition monitoring and diagnosis of GIS.

1.3 Problem Statement

The causes of defect occurrence inside a GIS could be due to many factors, such as poor machining during GIS manufacturing, vibration during transportation or assembly of GIS, undetected scratches on electrodes, poor electrical contacts, and mechanical abrasion movement of the conductor during load cycling [1, 5, 6, 54, 55]. The presence of defects results in the nuisance occurrence of partial discharges during GIS operation. There are several existing techniques used to detect the partial discharge occurrence in a GIS. A technique based on the detection of chemical by-products in a GIS as a result of partial discharge occurrence is still being studied by many researchers. In the studies, a chosen defect is purposely introduced inside the GIS so as to determine the resultant by-product gases. All of the introduced defects can be categorised as sole defect, that is, only one type of defect occurs at a given time. Examples of sole defects are a void in a solid dielectric, free conducting particles in the chamber, an electrode protrusion, and fixed conducting particles on a spacer. The effects of two defects occurring simultaneously are yet to be studied.

Apart from the limitation of using only a sole defect, previous studies are also limited in terms of experimental configuration, whereby only a plane-plane electrode configuration was used instead of a coaxial configuration which is more typical of a real GIS chamber. In terms of results, previous studies reported only a limited number of by-product gases, namely, thionyl fluoride (SOF_2), sulfuryl fluoride (SO_2F_2), tetrafluoromethane (CF_4), and carbon dioxide (CO_2). This could be due to the inferiority of the gas chromatography technique used for by-product gas detection [34-36].

A reliable partial discharge detection technique in a GIS using the by-product gas detection requires more practical results and analyses based on actual GIS configuration and all possible occurrences of defects. In view of the above-stated limitations, there is a need for a new study using an improved and more effective methodology to give the desired results.

1.4 Objectives

The main objective of this research is to develop an improved, effective, and more reliable method of gas analysis technique for condition monitoring and diagnosis of gas insulated switchgear. The specific objectives of this research are;

i. To formulate an experimental setup for partial discharge studies consisting of a prototype coaxial gas chamber typical to real life GIS, PD artificial defects, PD detector systems, and Fourier transform infrared spectrometer.
ii. To perform PD gas by-product experiments on three categories of defects, namely, sole, hybrid, and material dependent.
iii. To determine the correlation between PD by-product gases produced and the type of defect causing the PD.
iv. To propose and implement an accurate PD causing defect classification using a suitable pattern recognition algorithm.

1.5 Scope of Work

The scope of this research covers the staging of an experimental setup for partial discharge studies using a coaxial gas-insulated switchgear apparatus prototype and designed artificial defects. The defects used are limited to three categories, as mentioned above, to give a total of eight types of PD artificial defects. The gas detection only utilises the FTIR spectrometer technique. Defect classification is carried out using one technique, namely, the pattern recognition (random forest algorithm). However, eight different algorithms are investigated to determine the best among them.

1.6 Research Contributions

The main contributions of this thesis work are outlined as follows:

i. ***GIS Chamber Prototype for PD Studies***

This study has successfully formulated an experimental setup using a GIS coaxial chamber prototype typical to real life GIS with three categories of purposely introduced defects, namely, sole, hybrid, and material dependent defects. The chamber is capable of being energised up to 70 kV and pressurised up to 10 bars. A total of eight simulated defects are free conducting particle, electrode to dielectric void, electrode protrusion, fixed particle aluminium on the spacer, fixed copper on spacer, electrode protrusion-fixed copper particle hybrid, electrode protrusion-free copper particle hybrid, and electrode to dielectric void-free copper particle hybrid.

ii. ***Newly detected PD by-product gases***

The use of FTIR for gas analysis has enabled more by-product gases to be detected. A total of twelve gas by-products due to partial discharge activity in all defects were detected. Arranged according to significance, these are hexafluoroethane (C_2F_6), sulphur dioxide (SO_2), sulfuryl fluoride (SO_2F_2), octafluoropropane (C_3F_8), silicon tetrafluoride (SiF_4), thionyl fluoride (SOF_2), carbon monoxide (CO), disulfur decafluoride (S_2F_{10}), hydrogen fluoride (HF), tetrafluoromethane (CF_4), carbonyl sulphide (COS) and tetrafluoride (SOF_4).

iii. ***Detected harmful PD by-product gases***

The presence of CO, COS, SiF_4 and HF gases can be harmful to the GIS system due to their flammable and corrosive nature. Arranged according to significance, the most harmful gases are produced by the following defects: electrode protrusion-fixed copper particle hybrid, fixed copper particle, electrode protrusion-free copper particle hybrid and electrode protrusion.

iv. ***Defect classification using by-product gases pattern recognition***

The type, number, concentration, and chemical stability of by-product gases are found to be closely correlated to the type of defect. Generally the number and concentration of the by-product gases increases with electrical stress duration and the presence of the by-product gas and its concentration can be said to be an indication of a fault in GIS and the fault is harmful to the GIS. Further analyses using pattern recognition with eight algorithms based on the presence and concentration of the gas by-products were carried out. The random forest algorithm successfully recognises a given defect with an accuracy of 87.5%.

From the analyses using Waikato Environment for Knowledge Analysis (WEKA) workbench machine learning and data mining, in particular, the random forest algorithm of pattern recognition, the defect classification of sole, hybrid, and material dependent were successfully obtained with classification accuracies of 93.8%, 80%, and 96.4%, respectively. Therefore, the random forest algorithm can be applied as a very good tool for pattern recognition and prediction of multi-fault in a gas insulated system.

v. Random forest algorithm performance

Seven other algorithms of pattern recognition were investigated. The performance of the random forest algorithm is 1.5 times better than the next best algorithm. This research illustrates the feasibility and applicability of an effective GIS diagnostic using gas by-products analyses, in particular, using the random forest pattern recognition.

1.7 Thesis Outline

The outline of the thesis is described below.

Chapter 2 covers the literature review on diagnostic techniques of gas insulated switchgear, SF_6 basic properties, ionization phenomena and decomposition mechanism of SF_6 in gas insulated switchgear, genesis and diagnostic techniques for partial discharge detection, and an overview of pattern recognition classification using the model tree based algorithm, or random forest algorithm, in WEKA workbench.

Chapter 3 presents the research methodology which begins with the research design, procedure and experimental works, followed by the design of partial discharge artificial defects in three categories, namely, sole, hybrid, and material dependent defects. A total of eight different defects were designed. Detailed experimental procedures and procedures for pattern recognition of by-product gases for defect classification are described.

Chapter 4 reports all by-product gases detected for all defects. The types of gases and their concentrations are given in detail in the form of tables and graphical plots. Discussion is made on the newly found gases and their significance for each category of defect. Also, the chapter reports the results of intelligent defect classification using by-product gases pattern recognition. The WEKA software written in Java was used. The software contains tools for supervised machine learning and data mining. Several algorithms were used to classify the eight types of defects. The performance of random forest algorithm against seven other algorithms is reported.

Chapter 5 presents the conclusions obtained from this work and recommendation for future research work.

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APPENDIX A

LIST OF PUBLICATIONS

1. Ibrahim, V. M., Abdul-Malek, Z., and Muhamad, N. A. Status Review on Gas Insulated Switchgear Partial Discharge Diagnostic Technique for Preventive Maintenance. *Indonesian Journal of Electrical Engineering and Computer Science,* 2017. *7*(1): 9-17.
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